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Techniques for Evaluating the Nutritional Profile and Digestibility of Animal Feedstuffs by Different Laboratory Methods

Muhammad Asad Ur Rehman[1*] and Zeshan Zulfiqar[2]

[1]Department of Animal Nutrition, Sindh Agriculture University, Tandojam, Pakistan;[2]College of Animal Science and Technology, Henan Agricultural University Zhengzhou, China
*Corresponding author's email: phd-2k22-an-001@student.sau.edu.pk

Sustainable agriculture and food security are becoming global issues. Animal feed quality effects livestock production, thus improving it benefits. Adequate nutrition assessment of these feedstuffs is required to solve the issue. Worldwide, several methods are used with differing degrees of efficiency, scope, and accuracy. Proximate analysis and digestibility tests were frequently utilized to determine the nutritional value of cereals and forages. On the other hand, NIRS and enzyme-based tests were advanced. NIRS were applied for innovative feedstuff, insect proteins and algae. Similarly, enzyme-based tests give extensive knowledge but are difficult for standardization across species. This review focuses on applying traditional and advanced emerging technologies to evaluate feedstuffs' nutritional content and digestibility, particularly for ruminants. The growing use of novel feed ingredients emphasizes the need for adapting and standardizing these methods to ensure accurate evaluation. This review outlines the current state of laboratory techniques for assessing feedstuffs, identifies gaps in their application, and proposes future directions for integrating these methods into sustainable livestock systems. Refining and standardizing these techniques can improve feed efficiency, reduce environmental impacts, and support the development of more sustainable animal production practices.

Keywords: Proteins, amino acids, fodders, livestock, nutrients, proximate analysis, digestibility.

INTRODUCTION

Animal feed is a key component in livestock management. But it has a direct impact on animal health and productivity. Changing dietary patterns with the rising population increased the demand for animal products. The alteration of diets can enhance the performance and health of animals while simultaneously minimizing waste generation and environmental impact. For assessing the nutritional value of diet contents, it is urgent to develop precise and effective techniques (Araiza-Rosales *et al.*, 2022; Abid *et al.*, 2024). Various laboratory techniques simple to advance, such as proximate analysis to Near-infrared spectroscopy (NIRs) and enzyme-based assay, exist, but each method has its precision, intricacy, and implementation (Ma *et al.*, 2021; Siddiki *et al.*, 2022; Khan *et al.*, 2024). For instance, proximate analysis was used to determine fat, crude protein, and fibre while NIRs give a detailed analysis of feed composition (Mohamed and Chaudhry, 2008; Van Barneveld *et al.*, 2018; Bhatt *et al.*, 2023). However, its use in new feed components such as insect protein, algae, and other agriculture products is restricted (Rukundo, 2020; Beć *et al.*, 2022). With the increasing interest in alternative feed ingredients such as insect proteins, algae, and agricultural by-products—the need to adapt and standardize laboratory techniques has become urgent(Piercy *et al.*, 2023). These emerging feeds present potential solutions to the environmental challenges coupled to traditional livestock production, but their unique compositions often challenge conventional evaluation methods (Halmemies-Beauchet-Filleau *et al.*, 2018).

In vivo approaches are used to measure feed digestibility. However, they are laborious, time-consuming, and costly. In recent decades, researchers have developed quicker and cheaper in vitro and in situ methods for high-throughput analysis. The Ankom Daisy II Incubator simulates rumen fermentation and provides precise digestibility data for various diets (Bonta *et al.*, 2024). In vitro, gas generation methods have helped estimate feed environmental effects by measuring methane production during digestion(Romanzini *et al.*, 2020).

Despite feed evaluation advances, several difficulties remain. Advanced technologies enable thorough nutritional profiles,

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but cross-species standardization is challenging, and they are neglected in poultry and swine (Messad *et al.*, 2015; Veum *et al.*, 2017; Van Niekerk *et al.*, 2020; Wu *et al.*, 2020; Shurson *et al.*, 2021; Kumar *et al.*, 2023). Despite being cost-effective, in vitro approaches generally fail to simulate in vivo digestion, notably microbial interactions that affect nutrient absorption. This article discusses laboratory methods for estimating animal feedstuff nutritional composition and digestibility. It emphasizes their application to traditional and unique feeds. This study identifies shortcomings in existing approaches and proposes future research to improve feed assessment accuracy and efficiency, promoting sustainable livestock systems.

TRADITIONAL METHODS

***Proximate analysis*:** It is the most fundamental approach for assessing animal feed nutrition. It helps determine moisture, crude protein, crude fibre, fat, and ash levels (Hait *et al.*, 2023). This fast and accurate feed quality evaluation approach is used by many researchers (Hait *et al.*, 2023; Shovon *et al.*, 2024). Moreover, innovative diet such as insect-based chicken diets' protein content and Soy and fishmeal were also analysed through it (Bassett *et al.*, 2021; Ahmed and Nishida, 2023).

***Crude protein analysis*:** This technique was used to quantify nitrogen contents from feedstuff, which was further analysed to find the crude protein level in animal feeds (Sauvant *et al.*, 2023). This approach is also known for protein assessment. Its accuracy in measuring protein concentration across feed types makes the Kjeldahl technique popular (Patel *et al.*, 2024). Shovon. (2024) used the Kjeldahl technique to assess protein content in soybean meal and fishmeal(Shovon *et al.*, 2024). Although its application in feed quality assessments, like distinguishing between protein types or evaluating bioavailability, was restricted for some animal species, like

Table 1. Different fibre analysis methods.

Fibre Analysis Method	Description	Components Measured	Limitations	Sources
Neutral Detergent Fibre (NDF)	Measures the mass of undissolved material after treating feedstuff with a neutral detergent solution.	Cellulose, lignin, neutral sugar polysaccharides (arabinoxylans, β-glucans, galactans, galactomannans, mannans).	- Cannot measure pectic substances (limited for pectin-rich ingredients like legumes). - Fails to remove heat-denatured proteins, which can inflate fiber estimates.	(Van Soest and McQueen, 1973; Jung, 1997; Choct, 2015a; Choct, 2015b)
Acid Detergent Fibre (ADF)	Measures the mass of undissolved material after treatment with an acid detergent.	Cellulose, lignin, small and variable amounts of xylans and other components.	- Variable content makes the method less consistent across different feedstuffs. - Less valuable for cereals and oilseed meals.	(Jung, 1997)

Table 2. Describing bomb calorimetry method.

Aspect	Calorimetry	Elemental Analyzer with Empirical Models	Citations
Historical Justification	Historically considered expensive, complicated, and time-consuming due to the complexity of the equipment and experimental procedure.	Simpler and cheaper procedure for conducting proximate and structural analysis.	(Kathiravale *et al.*, 2003; Vargas-Moreno *et al.*, 2012; Shi *et al.*, 2016)
Current Equipment Availability	Commercially available calorimeters are now simple to use, requiring no more labour intervention than an elemental analyzer.	Used in combination with mathematical models for determining the Higher Heating Value (HHV).	
Cost of Equipment	Approx. €50,000.	Approx. €125,000 (more than twice the cost of a bomb calorimeter).	
Consumable Costs	Lower consumable costs.	Higher consumable costs compared to calorimetry.	
Labor Cost per Sample	Higher labor cost due to longer analysis time (20 min per sample).	Lower labor cost due to shorter analysis time (5 min per sample).	
Cost-Effectiveness (Per Sample)	Velázquez-Martí et al. (2017) found that direct determination using calorimetry was more expensive mainly due to labor cost.	23% cheaper (per sample) than direct determination using a bomb calorimeter.	
Capital Cost Considerations	Lower initial capital cost, making it potentially more attractive despite longer analysis time.	Higher initial capital cost but less time required per sample, which could be a deciding factor depending on the analysis volume.	
Accuracy of Measurement	Direct measurement improvements in process operations might offer higher accuracy.	Accuracy depends on the mathematical model and the analyzer's performance.	

monogastric, where amino acid content is necessary.

***Fiber analysis (NDF, ADF)*:** In feedstuff, fiber is also important. It helped to understand the ruminant digestibility and energy availability of fibre-rich diets. Fibre analysis, especially (Neutral Detergent Fibre) NDF and Acid Detergent Fibre (ADF) determining the structural carbohydrate content of forages and silage (Bedford *et al.*, 2023). Supplement NDF and ADF with microbial fermentation or in vitro digestibility assays can provide a complete feed utilization picture.

***Bomb calorimetry (Energy Content)*:** After basic nutritional analysis, energy content affects feed efficiency. By burning a sample and measuring the heat generated, bomb calorimetry accurately measures feedstuff gross energy content. This method is beneficial for assessing the energy-dense components like grains and oils (Palani *et al.*, 2023).

ADVANCED ANALYTICAL TECHNIQUES

***Near-Infrared Spectroscopy (NIRS)*:** Besides proximal analysis, NIRS can quickly analyze huge sample quantities. This quick, non-destructive analytical method evaluates animal feedstuffs for fiber, protein, and moisture content. This method's efficiency and accuracy in large-scale feed analysis have made it popular. NIRS was used to measure neutral detergent fiber (NDF) and acid detergent fiber in ruminant fodder and silage reported by many authors (Ohlsson *et al.*, 2007; Brogna *et al.*, 2018; Van Barneveld *et al.*, 2018; Piltz, 2023). For real-time feed quality testing, NIRS is recommended since it can examine large samples quickly without preparation. Calibration models for certain feed types restrict their application to new components without previous calibration. NIRS is beneficial for conventional feeds, however new feed components require further confirmation (Van Barneveld *et al.*, 2018; Ahmadi *et al.*, 2022).

***Amino Acid Profiling (HPLC)*:** Protein digestibility is important, and HPLC determined amino acid information for feed formulation. High-tech amino acid profiling quantifies feedstuff amino acids, revealing protein source quality. HPLC is often used to measure key amino acid concentrations and feed bioavailability.

***Fat Extraction (Soxhlet Method)*:** It is a traditional approach to extracting fat and lipids from diets. The solvents such as hexane and petroleum ether were used to extract lipids or fats from solid substances. This process demonstrates significant efficiency in fat removal but requires considerable time, such as several hours for full completion. The sample is sited in a thimble and washed many times with condensed solvent, effectively dissolving the fat and transferring it to a distinct flask. it is commonly utilized because of its efficiency but has limitations due to its reliance on solvents and the potential hazards of volatile organic compounds from solvents (Jia *et al.*, 2023; Kanwal and Musharraf, 2024; Mendez-Sanchez *et al.*, 2024; Shi *et al.*, 2024; Surma and Sadowska-Rociek, 2024).

***Gas Chromatography (Fatty Acid Profiling)*:** it is useful for algae or insect-derived components, which may have significantly different fatty acid compositions than standard diets. Various scientist investigated the fatty acid content of insect-based chicken feeds, demonstrating their potential as alternative fat sources. It helps to determine omega-three and omega-six, which are important for animal health. Due to its complexity and expenses, this approach's applicability is limited in research and feed formulation(Praveena *et al.*, 2024; Tognocchi *et al.*, 2024).

Digestibility Methods

Cost-effective and legal, in vitro digestibility assays measure feed digestibility without live animals. These methods are helpful in assessing novel feed ingredients. Recharla *et al.* (2019) tested grain-based diets for swine starch digestibility in vitro, while (Osorio, 2020) used the Tilley and Terry method to simulate ruminal and post-ruminal digestion,

Table 3. Describing amino acid profiling method.

Aspect	NIRS	HPLC
Purpose	Provides general information about protein digestibility.	Offers detailed amino acid profiles for accurate feed formulation.
Focus	Measures overall protein content.	Quantifies specific amino acids like lysine and methionine.
Key Application	Used for rapid analysis and screening in feed assessments.	Provides precise measurements of amino acids for protein quality evaluation.
Efficiency in Feed Formulation	Useful for quick assessments in routine analysis.	Critical for formulating monogastric diets, which require specific amino acid ratios.
Example Study	NIRS was used to measure neutral detergent fiber (NDF) and acid detergent fiber in ruminant fodder and silage (Ohlsson *et al.*, 2007; Brogna *et al.*, 2018; Van Barneveld *et al.*, 2018; Piltz, 2023)	HPLC to assess lysine and methionine in animal diets (Li *et al.*, 2024)
Cost & Equipment	Low-cost, accessible for routine use.	It is expensive and requires specialized equipment, limiting its use in commercial feed assessments.
Use in Industry	Commonly used for general feed assessments.	More restricted due to cost and complexity, but essential for high-precision formulation.
References	(Van Barneveld *et al.*, 2018; Ahmadi *et al.*, 2022)	(Tsiasioti and Tzanavaras, 2024)

revealing ruminant fodder digestibility. Conversely, live animals in in vivo digestibility assays measure nutrient absorption and excretion for the most reliable results (Streeter, 1969; Boisen and Eggum, 1991). Though complicated and costly, these feed digestibility experiments are the gold standard. Several investigators conducted in vivo

Table 4. Laboratory techniques for feed evaluation.

Laboratory technique	Purpose to measure	Feed type	Animal species	Efficiency	Key Findings/Outcomes	Citation
Near-Infrared Spectroscopy (NIRS)	Nutritional Profile - Fiber Content	Forage/Silage	Ruminants	High Efficiency (Rapid, Non-Destructive)	High precision in measuring fiber content	(Khan *et al.*, 2024)
In Vitro Digestibility Assay	Digestibility Analysis	Grain-Based Feed	Swine	Moderate Efficiency (Simulates Digestion)	Effective for simulating digestion of starch-based feeds	(Dhakal *et al.*, 2023)
Proximate Analysis	Nutritional Profile - Protein Content	Novel Feed Ingredients	Poultry	Moderate Efficiency (Comprehensive)	Comprehensive basic nutrient analysis	(Errico *et al.*, 2022)
Enzyme-Based Assay	Digestibility Analysis	Protein-Rich Feeds	General Livestock	High Efficiency (Targeted Analysis)	Highly accurate for evaluating protein digestibility	(Ringø *et al.*, 2016)
Microbial Fermentation	Digestibility and Fermentability	Agricultural By-Products	Ruminants	Low Efficiency (Labor-Intensive)	Detailed fermentation profiles, useful for ruminal fermentation	(Filik and Filik, 2021)
Gas Production System	Fermentability Evaluation	Forage/Silage	Ruminants	Moderate Efficiency (Time-Consuming)	Useful for predicting in vivo digestibility through gas kinetics	(Piercy *et al.*, 2023)
Van Soest Fiber Analysis	Nutritional Profile - Fiber Content	Forage/Silage	Ruminants	Moderate Efficiency (Detailed Fiber Analysis)	Effective for measuring neutral and acid detergent fiber fractions	(Pedrazzani *et al.*, 2024)
Bomb Calorimetry	Nutritional Profile - Energy Content	Grain-Based Feed	Poultry	Low Efficiency (Destructive Method)	Provides highly accurate measures of gross energy in feedstuffs	(Santos Jr, 2003)
In Situ Digestibility	Digestibility Analysis	Forage/Silage	Ruminants	Low Efficiency (Time-Consuming, In Vivo)	Highly accurate for simulating rumen digestibility	(Cheli *et al.*, 2012; Krizsan *et al.*, 2012)
Amino Acid Analysis	Nutritional Profile - Amino Acid Content	Protein-Rich Feeds	Swine	High Efficiency (Targeted Analysis)	Provides detailed amino acid profiles, essential for balancing diets	(Zhang *et al.*, 2019; Zhang *et al.*, 2022)
Gas Chromatography	Nutritional Profile - Fatty Acid Content	Novel Feed Ingredients	Poultry	High Efficiency (Detailed Fatty Acid Profile)	Excellent for profiling fatty acids in novel feed ingredients	(Leiva & Granados-Chinchilla, 2020)
Total Digestible Nutrients (TDN)	Digestibility and Energy Content	Agricultural By-Products	Ruminants	Moderate Efficiency (Common in Feed Trials)	Accurate for estimating total digestible energy available from feed	(Beck et al., 2024)
Dry Matter Digestibility (DMD)	Digestibility Analysis	Forage/Silage	Ruminants	Moderate Efficiency (Widely Used)	Standard method for assessing digestibility of forage feedstuffs	(Dejene, 2018)
Crude Protein Analysis	Nutritional Profile - Protein Content	Protein-Rich Feeds	General Livestock	Moderate Efficiency (Widely Available)	Widely used for evaluating crude protein in animal feedstuffs	(Kamal *et al.*, 2020)
Neutral Detergent Fiber (NDF)	Nutritional Profile - Fiber Content	Forage/Silage	Ruminants	Moderate Efficiency (Fiber Analysis)	Standard method for analyzing structural components of plants	(Zubillaga *et al.*, 2024)
Acid Detergent Fiber (ADF)	Nutritional Profile - Fiber Content	Forage/Silage	Ruminants	Moderate Efficiency (Fiber Analysis)	Effective in determining the digestibility of forage fiber	(Mosebi *et al.*, 2024)
Fat Extraction (Soxhlet Method)	Nutritional Profile - Fat Content	Protein-Rich Feeds	Poultry	Low Efficiency (Time-Consuming)	Precise but labor-intensive method for determining fat content	(Katoch, 2022)
In Vivo Digestibility Trials	Digestibility Analysis	General Feed Type	General Livestock	Low Efficiency (Labor-Intensive, Expensive)	Provides the most accurate data but is resource-intensive	(González *et al.*, 2023)
Indigestible Neutral Detergent Fiber (iNDF)	Digestibility Analysis	Forage/Silage	Ruminants	Moderate Efficiency (Widely Used)	Measures fiber fractions that are indigestible and resistant to fermentation	(Piltz, 2023)
Tilley and Terry Method	Digestibility Analysis	Forage/Silage	Ruminants	Moderate Efficiency (Widely Used)	Provides an in vitro method to estimate digestibility in ruminants	(Piltz, 2023)
Pepsin-HCl Method	Digestibility Analysis	Protein-Rich Feeds	Swine	Moderate Efficiency (Widely Used)	Used to measure the digestibility of protein in various feeds	(Papadopoulos, 1985)

studies with ruminants to confirm in vitro results, indicating that lab results transfer into real-world feed efficiency.

Protein digestibility can often be estimated quickly by assessing protein solubility in an acidic pepsin solution using the Pepsin-HCl method. This method works well for testing protein-rich diets for pigs and poultry. Allen et al. (2020) showed it can optimize protein intake in swine diets, replacing in vivo protein grade assessment. Gas and volatile fatty acid (VFA) generation during fermentation of feedstuffs must be determined with microbial and fermentation methods (Cone and Becker, 2012).For high-fiber diets like agricultural byproducts, such techniques give thorough rumen fermentation efficiency data (Chuang *et al.*, 2021). Another in vitro method analyzes feed fermentability by measuring gas generation (Getachew *et al.*, 1998; Rymer *et al.*, 2005). This method links gas production with digestibility and energy availability, which renders it ideal for screening large samples quickly (Hamid *et al.*, 2007). Many researchers used this system to evaluate forages and grain-based feeds, predicting in vivo digestibility (Escobar-Bahamondes *et al.*, 2017), but others noted that it may not fully capture the complex interactions between feed and animal metabolism. Finally, indigestible neutral detergent fiber (iNDF) study measures resistant fiber (Seal and Reynolds, 1993; Cammack *et al.*, 2018). High iNDF levels reduce digestion and feed efficiency ((Claassen, 2018).

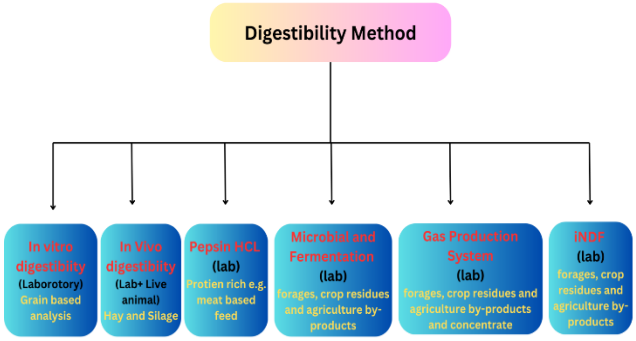

Figure 1. Describing digestibility method.

***Specialized or Emerging Techniques*:** There are three main emerging techniques used for feed nutrient analysis such as enzyme based essay, protein solubility test and total digestible nutrients. Enzyme-based assays Simulate animal digestion with enzymes like pepsin and trypsin to measure protein digestibility. It helps to optimise protein intake and reduce nitrogen excretion. It accurately simulates digestive processes, but it has limitations for different species' enzymes(Santos Jr, 2003; Recharla *et al.*, 2019; Ribeiro *et al.*, 2020; Helal *et al.*, 2023; Abid *et al.*, 2024; Bonta *et al.*, 2024). Protein Solubility Test helps to measure protein solubility in buffer solutions to evaluate digestibility and bioavailability(Lindberg *et al.*, 2024). It is a rapid indicator of protein bioavailability and is also effective for innovative feeds(Lasekan and Nayak, 2016). Total Digestible Nutrients (TDN) help to calculate total energy from digestible protein, fiber, and fat to assess overall feed quality. It is a simple and widely accepted method (da Cruz *et al.*, 2021).

***Critical Analysis*:** After reviewing the 87 review articles, the performance matrix was developed for different feed nutrient analysis techniques. Figure 2 summarizes these techniques and highlights the performance rating from 1 to 4. In vivo digestibility trial had the highest accuracy, but it was expensive with the lowest speed with less applicability for novel feeds.

Performance Matrix of Feed Evaluation Techniques
Proximate Analysis 3 1 1 1
Crude Protein (Kjeldahl) 2 2 3 2
Fiber Analysis (NDF, ADF) 2 1 3 1
Near-Infrared Spectroscopy 3 2 2 1
Amino Acid Profiling (HPLC) 1 3 3 3
In Vitro Digestibility Assays 3 1 2 2
In Vivo Digestibility Trials 1 3 4 3
Enzyme-Based Assays 2 2 3 2
Microbial Fermentation 1 3 3 2
Gas Production System 2 2 2 1
Fat Extraction (Soxhlet Method) 1 2 3 2
Gas Chromatography (Fatty Acid Profiling) 1 3 3 3
Total Digestible Nutrients (TDN) 2 1 2 1
Pepsin-HCl Method 3 1 2 2
Indigestible NDF Analysis 2 2 2 2
Techniques
Speed
Cost
Accuracy
Applicability to Novel Feeds
Criteria
Performance Rating (1-4)
4.0
3.5
3.0
2.5
2.0
1.5
1.0

Figure 2. Performance matrix of feed evaluation techniques.

***Conclusion*:** Traditional feed evaluation methods face challenges with novel ingredients like insect meal and algae. Moreover, future approaches should be used with other techniques like NIRS with precise methods like HPLC and Gas Chromatography. Additionally, integrating micro-biome analysis and machine learning will improve the accuracy of feed assessments. Hence, prioritizing sustainability will help align feed evaluation with eco-friendly agricultural goals.

***Authors' contributions*:** MAUR led the conceptualization, conducted the literature search, and wrote most of the manuscript. ZZ assisted with literature analysis, drafted the methodology, proofread and contributed to editing of this manuscript.

***Conflict of Interest*:** The authors affirm that there is no conflict of interest.

***Ethical statement*:** This review paper adheres to ethical guidelines and standards. All literature cited has been properly referenced, and no original research involving human or animal subjects was conducted.

Limitations and future direction

Aspect	Description	Impact/Challenges	Future Direction	Potential Benefits
Limited Calibration for Novel Feeds	Advanced methods like NIRS and Gas Chromatography require specific calibration models for traditional feed ingredients, which aren't readily available for novel feed ingredients like insect proteins, algae, and agricultural by-products.	Lack of comprehensive calibration datasets reduces accuracy when assessing new feed sources, leading to misinterpretations of feed quality.	Develop large, standardized datasets and calibration models for novel feed ingredients. Machine learning can be used to improve model accuracy.	Improved accuracy for emerging feed ingredients using methods like NIRS and Gas Chromatography across a broader range of feed types.
Resource-Intensive Nature of In Vivo Trials	In vivo digestibility trials, though highly accurate, are labor-intensive, expensive, and time-consuming due to the need for live animals, long trial durations, and extensive facilities.	High costs and time requirements make these trials unsuitable for routine feed evaluation, limiting their use to validating new feeds or confirming lab findings.	Reduce reliance on in vivo trials by developing hybrid techniques, integrating in vitro assays with in silico models and rapid screening methods.	More efficient and balanced solutions for large-scale feed evaluations with reduced labor and costs, maintaining accuracy.
In Vitro and In Silico Simulation Gaps	In vitro methods (e.g., Pepsin-HCl assays) simulate digestion but cannot replicate the complexity of in vivo digestion, including microbial interactions and species-specific differences. In silico models provide theoretical predictions, but fail to account for nutrient bioavailability and absorption variability seen in live animals.	Incomplete simulation of real-world digestion and nutrient absorption, leading to gaps in the accuracy of feed quality predictions.	Hybrid approaches that blend in vitro methods with in silico modeling and advanced enzyme-based assays could better replicate digestion complexity.	Improved accuracy and efficiency in feed evaluation by reducing the gap between simulated and real-world digestion processes.
Cost and Complexity of Advanced Techniques	Techniques like Gas Chromatography for fatty acid profiling and Amino Acid Profiling (HPLC) provide high-precision results but are expensive, require specialized expertise, and rely on complex equipment.	High cost and technical requirements make these methods less accessible for routine feed analysis, especially in small-scale or developing operations.	Implement automation and high-throughput capabilities to streamline the application of these techniques, making them more efficient and cost-effective.	More accessible advanced techniques for large-scale operations, with reduced labor and cost burdens.
Microbiome Integration in Digestibility Studies	Microbial fermentation plays a key role in nutrient absorption in animals, but most current digestibility studies do not incorporate microbiome analysis.	Limited understanding of how gut flora interacts with feed ingredients, potentially missing key insights into feed utilization.	Integrate microbiome profiling with existing in vitro and in vivo digestibility studies.	Deeper understanding of nutrient absorption and digestion mechanisms, leading to more accurate assessments of feed quality.
Environmental Sustainability	The environmental impact (e.g., carbon footprint, methane production) of feed ingredients is increasingly important for sustainable livestock production, but current methods focus on feed quality rather than environmental effects.	Lack of assessment of environmental sustainability in feed evaluation, limiting the ability to make eco-friendly feed choices.	Focus on evaluating environmental impacts of different feeds, including novel ingredients, to guide sustainable livestock practices.	More eco-friendly feed options and reduced environmental impact of livestock production.

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